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Formation of *Trans* Fatty Acids in Ground Beef and Frankfurters due to Irradiation

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ABSTRACT: This study was conducted to investigate possible formation of *trans* fatty acids due to irradiation of ground beef and frankfurters. Ground beef and frankfurter samples were irradiated at doses of 0, 1, and 5 kGy at 4 °C, and stored at 4 °C for 7 d (ground beef) or 3 mo (frankfurters). After irradiation and storage of the samples, *trans* fatty acids along with other fatty acids were analyzed using a modification of AOAC method 996.01. The results showed that 1 kGy irradiation did not induce any change in *trans* fatty acid content. However, 5 kGy irradiation caused a small but statistically significant ($P < 0.01$) increase in the dominant *trans* fatty acid, C18:1 *trans*, which increased from 3.99% (of total fatty acid) for the nonirradiated ground beef to 4.05% for the 5 kGy sample, and from 1.21% for the nonirradiated frankfurter to 1.28% for the 5 kGy sample. Irradiation had no apparent effect on C16:1 and C18:2 *trans* fatty acids. In addition, irradiation slightly decreased the relative amount of poly-unsaturated fatty acid of ground beef and frankfurters, particularly after storage. Compared to variations in *trans* fatty acid content and fatty acid composition occurring naturally in meat and meat products, the changes due to irradiation were negligible.

Keywords: fatty acid, frankfurter, ground beef, irradiation, *trans* fat

Introduction

It has been demonstrated that a positive relationship exists between consumption of *trans* fatty acids and low-density lipoprotein cholesterol and a negative relationship between *trans* fatty acids and high-density lipoprotein cholesterol, suggesting that consumption of *trans* fatty acids increases the risk of coronary heart disease (Pietinen and others 1997; Hunter 2005). As a result, health organizations and the U.S. federal government have recommended consumers minimize their intake of *trans* fatty acids. Most *trans* fatty acids are present in processed foods as part of hydrogenated or partially hydrogenated vegetable oils added as ingredients. However, a small amount of *trans* fat occurs naturally in dairy and some meat products, such as beef and lamb, as a result of biohydrogenation.

Ionizing radiation is a processing technology used to improve the microbial safety and to extend shelf life of various foods. Currently, irradiation is permitted by USDA, FSIS, and U.S. FDA at doses up to 4.5 kGy for treating refrigerated, uncooked meat and meat by-products (FSIS 1999). Doses commonly used commercially in food irradiation are much lower than 4.5 kGy (Fan 2006). Irradiation of ready-to-eat meat products (such as frankfurters) has not been approved. However, a petition being considered by FDA, if approved, would allow use of ionizing radiation to treat a variety of ready-to-eat products to a maximum irradiation dose of 4.5 kGy in a nonfrozen state (FDA 2000). Although FDA and many other health organizations have concluded that irradiation does not induce chemical changes that enhance toxicological, or nutritional hazards beyond those brought about by conventional food processing techniques, 2 recent studies reported that irradiation increased the amounts of *trans* fatty acids in ground beef. Brito and others (2002) irradiated ground beef to doses up to 8 kGy at room temperature with a dose rate of 5.8 kGy/h. They found that the *trans* fatty acid content of ground beef increased as radiation dose increased. The *trans* fatty acid content increased from 4.6% (of total fatty acid) for the nonirradiated sample to 8.0% for 1 kGy sample, a 74% increase. Further increase in radiation doses to 5 kGy did not appreciably increase *trans* fatty acid content. More recently, Yilmaz and Geçgel (2007) also found significant increases in *trans* fatty acid content of ground beef at doses of 3 kGy or above. At 5 kGy, total *trans* fatty acid content was increased from 7.0% to 9.4%, a 34% increase. In contrast, Chen and others (2007) found no significant effect of irradiation (0 to 3.2 kGy) on the C18:1 *trans* content of the total lipid fraction of beef semitendinosus muscle; however, some changes occurred in the much lower concentrations of C16:1 *trans* and C18:2 *cis, trans* content of the neutral and polar lipid fractions. Irradiation of barley grains (Geißler and others 2003) with a dose of 10 kGy resulted in no measurable *trans* isomers. From the studies on beef muscle and ground beef, the impact of irradiation on the total *trans* fatty acid content of beef lipid is not clear. Furthermore, the impact of irradiation on the *trans* fatty acid content of frankfurters has not been reported. The objective of the present study was to investigate possible formation of *trans* fatty acids and changes in other fatty acids in ground beef and frankfurters due to irradiation. Since the variation in results among studies may be due to differences in methods, we selected and modified an AOAC official fatty acid separation and quantification technique (AOAC 2002) to determine the impact of irradiation on *trans* fatty acids.

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Materials and Methods

Meat samples and sample preparation

Fresh 80% lean, 20% fat Angus ground beef (PGA Beef Inc., Austin, Tex., U.S.A.) was re-ground using a meat grinder (Model nr MG1532, Hobart Manufacturing Co., Troy, Ohio, U.S.A.) to achieve uniformity. Aliquots (approximately 454 g) of the ground beef were then placed on retail foam trays (7.5 × 12.5 cm, Pactiv Co, Lake Forest, Ill., U.S.A.) and covered with stretch oxygen permeable film (Ominfilm, Pliant Co., Uniontown, Ohio, U.S.A.). Frankfurters were purchased from Hatfield Quality Meats (Hatfield, Pa., U.S.A.). Major ingredients of the frankfurters were pork, mechanically separated turkey, beef, and hydrolyzed beef stock along with chemicals. The fat content of the frankfurter samples was 25.6 ± 0.8% (w/w). There were 10 frankfurters in each package with a total weight of approximately 454 g (1 lb). There were 4 replicate packages of ground beef and frankfurters for each treatment and storage level.

Both ground beef and frankfurters were irradiated at 4 °C to doses of 1 and 5 kGy. Nonirradiated (0 kGy) samples served as controls. Detailed description of irradiation and dosimetry is given in the following section. After irradiation, ground beef and frankfurter samples were either immediately frozen at −20 °C and shipped or stored at 4 °C for 7 d (ground beef) and 3 mo (frankfurters), then frozen at −20 °C and shipped. All samples were shipped on dry ice overnight to the USDA, ARS, Richard B. Russell Agricultural Research Center, Athens, Ga., U.S.A. in insulated boxes. After being received, ground beef samples were stored at −20 °C (1 to 5 d) until homogenization and analysis. Previous work with cereal products established that there were no changes in *trans* fat content at −20 °C for at least 7 d (Kim and others 2007). Ground beef samples were homogenized daily, 1 replicate per day, after thawing, using a Robot Coupe homogenizer (Blixer 3 model, Robot Coupe USA Inc., Joliet, Ill., U.S.A.) until a smooth and consistent texture was obtained, and analyzed for fatty acids content on the same day. For frankfurters, samples were homogenized, immediately after arrival, using the Robot Coupe homogenizer, stored at 4 °C and analyzed for fatty acids daily, 1 replicate per day, within 7 d of homogenization.

Irradiation and dosimetry

Irradiation was conducted using a self-contained, Lockheed Corp. ^{137}Cs gamma radiation source (Marietta, Ga., U.S.A.). The unit has 23 ^{137}Cs rods placed in an annular array around a 63.5-cm-high stainless steel cylindrical chamber with a 22.9-cm internal diameter. The dose rate was 0.086 kGy/min, which was established using alanine transfer dosimeters from the Natl. Inst. of Standards and Technology (Gaithersburg, Md., U.S.A.). Corrections for source decay were made monthly. Variations in radiation dose absorption were minimized by placing the samples within a uniform area of the radiation field, and by using the same geometry for sample irradiation during the entire study. The 5-mm-dia alanine dosimeters were placed into 1.2 mL cryogenic vials (Nalgene, Rochester, N.Y., U.S.A.), and the cryogenic vials were taped onto the samples prior to irradiation. After irradiation, the free-radical signals in the dosimeters were measured using a Bruker EMS 104 EPR Analyzer (Bruker Instruments, Rjeomstettem, Germany). Temperature (4 ± 2 °C) in the radiation chamber was maintained by injecting the gas phase from a liquid nitrogen tank into the radiation chamber. Targeted doses were 0, 1, and 5 kGy. Measured doses were within 10% of the target doses. Maximum/minimum dose ratio was 1.2.

Analysis of fatty acids

Fatty acids, including *trans* and total fatty acids were measured in homogenized ground beef and frankfurters using a modification of AOAC official method 996.01 (AOAC 2002; Kim and others 2007). The modifications consisted of a longer GC column (100 m compared with 30 m) and operation of the GC with temperature programming that improved separation of *trans* and *cis* isomers. Briefly, duplicate aliquots of each sample were weighed into Mojonnier tubes and 1 mL of 10 mg/mL tritridecanoin (C13:0, T-3882, Sigma, St. Louis, Mo., U.S.A.) in chloroform was added as an internal standard. Sample size was between 0.8 and 1.0 g for ground beef and between 0.7 and 0.8 g for frankfurters based on total fat values of the products (provided by the manufacturer) of 20% and 26%, respectively. Each sample was digested with hot 8 N HCl and ethanol for 40 min and the hydrolyzed fat components were subsequently extracted 3 times with diethyl and petroleum ethers. The diethyl and petroleum ethers were evaporated on a steam bath and the extracts saponified and esterified (AOAC 2002). The fatty acid methyl esters (FAME) formed were analyzed in parallel with FAME standards (Supelco 37 Component FAME Mix, Supelco, Bellefonte, Pa., U.S.A.) using an Agilent 6890N gas chromatogram (Agilent Technologies Inc., Palo Alto, Calif., U.S.A.) with an SP-2560 flexible fused silica capillary column (100 m × 0.25 mm internal dia × 0.2 μm film thickness, Supelco). Helium was the carrier gas with a linear velocity of 18 cm/s. The split ratio was 50:1. A single injection of 1 μL was made per sample duplicate. The injection port and detector (flame ionization detector) were kept at 200 and 250 °C, respectively, with gas flows of 40 mL/min for hydrogen and 450 mL/min for air. Oven temperature programming consisted of an initial temperature of 120 °C held for 5 min, an increase in temperature of 3 °C/min to 240 °C and a hold time of 20 min at 240 °C. Sample FAME were measured against the C13:0 internal standard; Supelco 37 Component FAME mix was used in the identification and quantification of individual fatty acids according to their percentage areas. The FAME of C18:1 and C18:2 *trans* and *cis* fatty acids were assigned by comparison of retention times with standard FAME including elaidic acid methyl ester (*t*-9-octadecanoic acid, C18:1t), oleic acid methyl ester (*c*-9-octadecanoic acid, C18:1c), linolelaidic acid methyl ester (*t*-9, *t*-12-octadecadienoic acid), and linoleic acid methyl ester (*c*-9, *c*-12-octadecadienoic acid); and according to Ratnayake and Pelletier (1992), AOCS Method Ce 1h-05 (2005) and Aldai and others (2006). The peak identified by comparison of retention time with elaidic acid methyl ester was broad compared to other peaks (Figure 1 and 2) and considered to be made up of two or more C18:1 *trans* isomers (Ratnayake and others 2006). This peak was reported as total C18:1 *trans*. The FAME peaks identified as corresponding to *c*-9-octadecanoic acid (oleic acid methyl ester) and c-11-octadecanoic acid (*cis* vaccenic acid methyl ester) were combined and reported as total C18:1 *cis* (Figure 1 and 2). Total fatty acid was reported as percent of sample weight and individual fatty acids were expressed as percent of total fatty acids weight. In addition, C18:1 *trans* was also expressed as percent of sample weight. Infant formula (SRM 1846, Natl. Inst. of Standards and Technology) was used as a standard reference material for total fat, on a daily basis.

Statistical analysis

The experiments were performed as a completely randomized block design consisting of 3 irradiation treatments, 2 storage times, and 4 replicates. Data were analyzed using statistical software (SAS, version 8.2, SAS Inst. Inc., Cary, N.C., U.S.A.). Standard deviations were calculated using the same software. The effects of irradiation doses and storage as well as interactions between irradiation dose

and storage were analyzed using a generalized linear model and Duncan's multiple range test ($P < 0.01$).

Results and Discussion

Ground beef

C18:1 *trans* was the dominant *trans* fatty acid in ground beef as shown in many other studies (that is, Enser and others 1998; Aldai and others 2006; Chen and others 2007) (Figure 1). The broad GC peak for C18:1 *trans* was considered to be made up of two or more C18:1 *trans* isomers. Although the individual isomers were not identified in this study, Aldai and others (2006) found that C18:1n11 *trans* (*trans* vaccenic acid) was the predominant isomer in beef muscle with smaller quantities of C18:1n10 *trans* and C18:1n9 *trans* (elaidic acid). Using palmitelaidic acid (9-*trans*-hexadecanoic acid; Nucheck, Elysian, Minn., U.S.A.) as an additional external standard, a minor peak that consistently occurred in all the chromatograms was identified as the fatty acid methyl ester of C16:1 *trans* fatty acid. Other *trans* fatty acids present in the ground beef samples were identified as 18:2 *trans* fatty acid (multiple isomers). The 18:2 *trans* isomers for this study were defined as isomers containing 1 or 2 *trans* double bonds. Because the peaks for 16:1 and C18:2 *trans* fatty acids were very small (less than 10% of the total *trans* fatty acids), we did not calculate the absolute amount of these *trans* fatty acids. Instead, they were expressed as a ratio of peak areas of *trans* isomers over corresponding *cis* isomers (C16:1*trans*/C16:1*cis* and C18:2*trans*/C18:2*cis*).

When expressed as the percentage of total sample weight, the dominant *trans* fatty acid (C18:1*trans*) content was not consistently affected by irradiation at either dose (Table 1). However, when

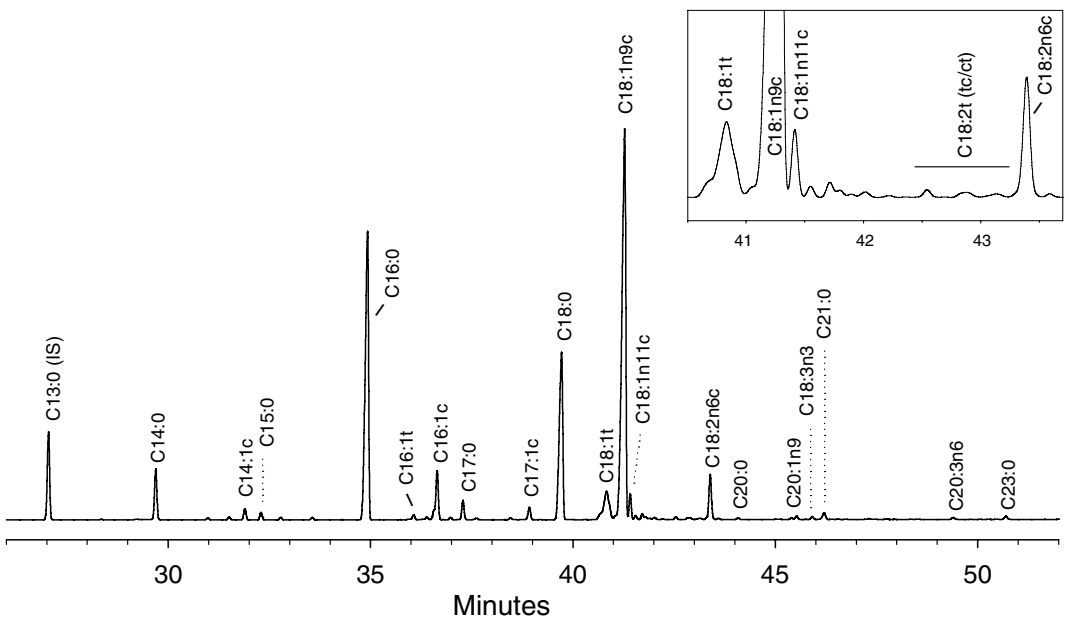

Figure 1—Gas chromatogram of the FAME of ground beef fatty acids. Analysis involved acid digestion of homogenized ground beef, extraction of lipids, and saponification and esterification of the fatty acids followed by gas chromatography using a SP-2560 flexible fused silica column (100 m × 0.25 i.d.) and temperature programming as described in the text. The insert is a magnification of the C_{18} region. C13:0 (IS) was the internal standard.

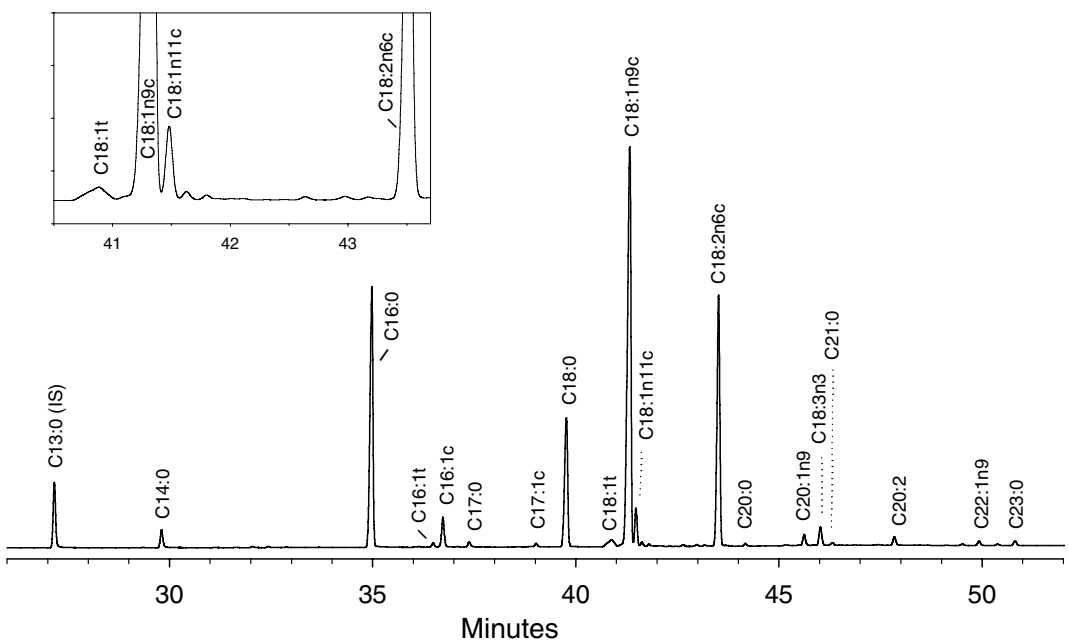

Figure 2—Gas chromatogram of the FAME of frankfurter fatty acids. Analysis involved acid digestion of homogenized frankfurters, extraction of lipids, and saponification and esterification of the fatty acids followed by gas chromatography using a SP-2560 flexible fused silica column (100 m × 0.25 i.d.) and temperature programming as described in the text. The insert is a magnification of the C_{18} region. C13:0 (IS) was the internal standard.

expressed as the percentage of total fatty acids, a slight but statistically significant increase in the *trans* fatty acid was observed in 5 kGy samples. The lower dose (1 kGy) of irradiation did not cause any change in C18:1 *trans* fatty acid. The ratio of the peak area of C16:1 *trans* fatty acid methyl ester to the peak area of C16:1 *cis* fatty acid methyl ester did not change with irradiation treatment ($P > 0.05$). Furthermore, the C18:2 *trans*/C18:2 *cis* ratios of irradiated ground beef samples were similar to those of nonirradiated samples, suggesting that the C16:1 and C18:2 *trans* fatty acids were not significantly ($P > 0.01$) affected by irradiation. These results are similar to those of Chen and others (2007) who found no changes in percentages of *trans* fatty acids in the total lipid fraction of beef intramuscular lipid after irradiation with 1.1 to 3.2 kGy. Isomers reported were C16:1 *trans*, C18:1 *trans* and C18:2 *cis*, *trans* with the C18:1 *trans* (1.2% to 1.3% of total fatty acids) being the most abundant. Yilmaz and Geçgel (2007) found no increase in total *trans* fat of ground beef at a dose of 1 kGy but an increase of 35% (of total fatty acids) after 5 kGy of irradiation. It was not indicated in that study how the *trans* fatty acids were identified. Brito and others (2002) found an increase of 74% *trans* fat starting at 1 kGy with an increase of 85% at 5 kGy; again it was not indicated how the *trans* fat was identified. The increase in *trans* fatty acids of ground beef due to irradiation observed in the present study was only 1.5% to 2% (expressed on a percentage of total fatty acids basis).

It is unclear what contributes to the differences in *trans* fatty acid formation due to irradiation between the present study and the 2 earlier studies (Brito and others 2002; Yilmaz and Geçgel 2007). In the earlier studies, there was no reference of any official method, or detailed description about fatty acid analysis, such as sample size, storage condition, identification of *trans* fatty acids, and how fatty acids were extracted or analyzed. Neither of the publications showed chromatograms or retention times of fatty acids, or specified how GC peaks were assigned. Yilmaz and Geçgel (2007) used a short (50 m) column which could make it difficult to achieve good separation of *cis*/*trans* isomers. In the present study, we employed an AOAC method and found that irradiation at doses up to 5 kGy had a very limited effect on *trans* fatty acid content.

In the current study, the amount of total fatty acids in ground beef was not affected by irradiation. Irradiation (5 kGy), however, reduced the total unsaturated fatty acids (TUFA), mainly due to the reduction in poly-unsaturated fatty acids (PUFA) as irradiation had no significant effect on mono-unsaturated fatty acids (MUFA). In addition, total saturated fatty acids (TSFA) increased with increasing radiation dose. The increase in TSFA was due to the increases in C15:0, C16:0, and C18:0, particularly after 7 d of storage. Another study (Chen and others 2006) also found that irradiation (1.13 to 3.17 kGy) increased TSFA (mainly C16:0) in beef intramuscular lipid. As a result of the overall increase in TSFA and the decrease in TUFA in the current study, the ratio of TUFA to TSFA decreased with increasing irradiation doses. Chen and others (2007) found that PUFA of beef meat was reduced by irradiation (1.13 to 3.17 kGy) while Formanek and others (2003) showed that irradiation (4 kGy) caused a significant reduction in the PUFA content of minced beef, mainly in C18:2 after storage at 4 °C under fluorescent light for 8 d. The reduction in PUFA resulted in a decrease in the ratio of PUFA to TSFA in lamb and beef meat (Kanatt and others 2006; Chen and others 2007). It should be pointed out that the changes in fatty acids observed in the present study were very small even though the changes were statistically significant ($P < 0.01$). For example, 5 kGy samples had TUFA of 53.35% of total fatty acid after 7 d of storage. Compared to the control (53.58% of total fatty acid), the increase was only about 0.4%.

Table 1—Changes in fatty acid composition of ground beef either not irradiated (0 kGy) or irradiated with 1 and 5 kGy gamma rays.

	0 d			7 d		
Fatty acid	**0 kGy**	**1 kGy**	**5 kGy**	**0 kGy**	**1 kGy**	**5 kGy**
C14:0	3.20 ± 0.01 ab[A]	3.21 ± 0.01 ab	3.21 ± 0.01 ab	3.19 ± 0.01 b	3.20 ± 0.01 ab	3.21 ± 0.01 a
C14:1c	0.73 ± 0.00 a	0.73 ± 0.01 a	0.73 ± 0.00 a	0.73 ± 0.00 a	0.73 ± 0.01 a	0.73 ± 0.00 a
C15:0	0.47 ± 0.00 bc	0.47 ± 0.00 ab	0.47 ± 0.00 ab	0.46 ± 0.00 c	0.47 ± 0.00 bc	0.47 ± 0.00 a
C16:0	25.51 ± 0.04 bc	25.55 ± 0.03 ab	25.61 ± 0.03 a	25.27 ± 0.04 e	25.34 ± 0.05 d	25.46 ± 0.02 c
C16:1c	3.69 ± 0.01 b	3.69 ± 0.01 b	3.69 ± 0.01 b	3.82 ± 0.01 a	3.82 ± 0.00 a	3.82 ± 0.01 a
C17:0	1.29 ± 0.00 c	1.29 ± 0.00 c	1.29 ± 0.00 c	1.30 ± 0.01 b	1.31 ± 0.00 b	1.32 ± 0.01 a
C17:1c	0.81 ± 0.00 a	0.81 ± 0.00 a	0.81 ± 0.00 a	0.81 ± 0.00 a	0.81 ± 0.00 a	0.81 ± 0.00 a
C18:0	15.41 ± 0.02 ab	15.44 ± 0.05 a	15.46 ± 0.01 a	15.32 ± 0.03 c	15.36 ± 0.02 bc	15.44 ± 0.03 a
C18:1t	3.99 ± 0.01 d	4.01 ± 0.03 d	4.05 ± 0.01 c	4.34 ± 0.01 b	4.36 ± 0.02 b	4.43 ± 0.02 a
C18:1t (% of sample)	0.69 ± 0.01 c	0.73 ± 0.02 b	0.71 ± 0.01 bc	0.78 ± 0.01 a	0.76 ± 0.02 a	0.78 ± 0.02 a
C18:1c	40.39 ± 0.03 a	40.34 ± 0.03 a	40.29 ± 0.06 ab	40.23 ± 0.04 bc	40.21 ± 0.05 bc	40.16 ± 0.04 c
C18:2n6c	3.06 ± 0.01 a	3.04 ± 0.01 ab	3.00 ± 0.01 b	3.08 ± 0.03 a	3.01 ± 0.04 b	2.88 ± 0.03 c
C20:0	0.10 ± 0.00 a	0.10 ± 0.00 a	0.10 ± 0.00 a	0.10 ± 0.00 a	0.10 ± 0.00 a	0.10 ± 0.00 a
C20:1n9	0.23 ± 0.00 a	0.23 ± 0.00 a	0.23 ± 0.00 a	0.22 ± 0.00 ab	0.22 ± 0.00 ab	0.22 ± 0.00 b
C18:3n3	0.19 ± 0.00 a	0.19 ± 0.00 ab	0.18 ± 0.00b	0.19 ± 0.00 a	0.18 ± 0.00 b	0.17 ± 0.00c
C21:0	0.53 ± 0.01 a	0.53 ± 0.01 a	0.50 ± 0.01 b	0.52 ± 0.01 ab	0.50 ± 0.02 b	0.44 ± 0.01 c
C20:3n6	0.15 ± 0.00 ab	0.14 ± 0.00 ab	0.14 ± 0.00 ab	0.16 ± 0.02 a	0.14 ± 0.00 b	0.13 ± 0.00 b
C23:0	0.26 ± 0.01 a	0.25 ± 0.01 ab	0.24 ± 0.01 b	0.26 ± 0.01 a	0.24 ± 0.01 b	0.20 ± 0.00 c
Total FA (% of sample)	17.41 ± 0.25 b	18.19 ± 0.40 a	17.63 ± 0.21 ab	18.01 ± 0.23 ab	17.49 ± 0.41 ab	17.60 ± 0.39 ab
MUFA	49.84 ± 0.03 b	49.80 ± 0.04 b	49.80 ± 0.05 b	50.15 ± 0.05 a	50.16 ± 0.04 a	50.17 ± 0.01 a
PUFA	3.40 ± 0.02 ab	3.37 ± 0.02 bc	3.32 ± 0.02 c	3.43 ± 0.03 a	3.33 ± 0.04 c	3.18 ± 0.03 d
TUFA	53.24 ± 0.03 d	53.17 ± 0.04 de	53.12 ± 0.05 e	53.58 ± 0.03 a	53.49 ± 0.04 b	53.35 ± 0.03 c
TSFA	46.76 ± 0.03 b	46.83 ± 0.04 ab	46.88 ± 0.05 a	46.42 ± 0.03 e	46.51 ± 0.04 d	46.65 ± 0.03 c
TUFA/TSFA	1.14 ± 0.00 d	1.14 ± 0.00 de	1.13 ± 0.00 e	1.15 ± 0.00 a	1.15 ± 0.00 b	1.14 ± 0.00 c
C16:1t/C16:1c	0.17 ± 0.00 a	0.17 ± 0.00 a	0.17 ± 0.00 a	0.17 ± 0.00 a	0.17 ± 0.00 a	0.17 ± 0.00 a
C18:2t/C18:2c	0.26 ± 0.01 a	0.26 ± 0.00 a	0.25 ± 0.03 a	0.26 ± 0.00 a	0.27 ± 0.01 a	0.28 ± 0.01 a

Notes: The samples were stored at 4 °C for 7 d after irradiation. Fatty acids were expressed as percentages of total fatty acids unless otherwise stated.
[A]The numbers are means followed by standard deviations ($n = 4$). Means with same letter within the same rows are not significantly different (Duncan's multiple range test, $P < 0.01$).
MUFA = mono unsaturated fatty acid; PUFA = poly unsaturated fatty acid; TUFA = total unsaturated fatty acid; TSFA = total saturated fatty acid.

Irradiation, in the current study, had the largest effect on C18:2n6c, C18:3n3, C21:0, and C23:0 fatty acids, particularly after 7 d of storage. It seems that irradiation and storage had an interactive effect on fatty acid composition. For example, on day 0, C18:2n6 *cis*, C18:3n3, and C23:0 fatty acids were only slightly reduced by 5 kGy irradiation. After storage, the effect of irradiation on those fatty acids was amplified. Even at 1 kGy, the percent of these fatty acids was reduced.

While irradiation at 5 kGy increased TSFA in ground beef, response of individual fatty acids to irradiation was different. For example, the concentration of shorter chain saturated fatty acid, C16:0 was increased in ground beef by irradiation (5 kGy), but the concentration of longer chain saturated fatty acids (C21:0 and C23:0) was decreased.

Frankfurters

Similar to ground beef, the dominant *trans* fatty acid in frankfurters was C18:1 *trans* and again the peak was broad indicating a mixture of several C18:1 *trans* isomers (Figure 2). The levels of C18:1 *trans* (0.29% to 0.31% of samples and 1.21% to 1.30% of total fatty acid) were much lower than those in ground beef even expressed as percentages of total fatty acid. The ingredients of the frankfurters in order of magnitude included pork, turkey, and ground beef. Pork and turkey are reported to have much lower amounts of *trans* fatty acids than beef (USDA 1995). *Trans* fatty acids occur naturally in ruminant animals, such as beef, whereas *trans* fat in pork or turkey will be present as a result of *trans* fat in the feed. Similar to ground beef, C16:1 *trans* was identified in frankfurters and calculated as the ratio of C16:1 *trans* to C16:1 *cis* (based on peak areas). The C18:2 *trans* fatty acid isomers are not presented in Table 2 as they were present in trace amounts; they were estimated to be $< 0.002\%$ of the product with ratios of the sum of C18:2 *trans isomers* to C18:2n6 *cis* of < 0.02.

Irradiation at 5 kGy caused a very small but statistically significant ($P < 0.01$) increase in C18:1 *trans* fatty acids when expressed as a percentage of either total fatty acid or sample (Table 2). Irradiation at 1 kGy did not affect the *trans* fatty acids content at all and C16:1 *trans*/C16:1 cis ratio was not affected by irradiation. This is the 1st report of the impact of irradiation on *trans* fat content of frankfurters.

Irradiation at either dose had no effect on the amount of total fatty acid in frankfurters. MUFA and TSFA were not affected by irradiation. PUFA were decreased by 5 kGy irradiation after 3 mo of storage due to the decrease in C18:2n6c fatty acid. Although this study and others (Formanek and others 2003; Kanatt and others 2006; Chen and others 2007) found a reduction of PUFA content in beef products, Jo and others (2002) did not find any change in the profile of fatty acids in pork sausages due to irradiation. Our results also suggested that in frankfurters, the effects of irradiation on the fatty acids were less profound, overall, than in ground beef. Frankfurters contained some antioxidants, such as sodium erythorbate, sodium nitrite, and spices. These antioxidants may reduce radiolysis of other food components (Ouattara and others 2002; Fan and Sommers 2006) by minimizing lipid oxidation and reacting with free sulfhydryl radicals. Mahrour and others (2003) found that irradiation decreased levels of unsaturated fatty acid of chicken legs; however, linoleic acid (C18:2) and arachidonic acid (C20:4) of marinated (with thyme and rosemary extracts) chickens irradiated with 5 kGy were significantly higher than those without the marinating treatment. Antioxidants such as rosemary extract and tocopherol were effective at inhibiting the changes in fatty acid due to irradiation of minced beef (Formanek and others 2003). Therefore antioxidants in frankfurters might minimize the change in fatty acids.

Compared to the natural variation in *trans* fat content of ground beef, the slight increase in *trans* fat by 5 kGy irradiation in ground beef was virtually negligible. There was about 0.06% to 0.09% (of total fatty acids) net increase in *trans* fatty acid caused by 5 kGy irradiation. Similarly for frankfurters there was a 0.07% net increase. However, the variations in *trans* fatty acid content occurring naturally were tens to hundreds of times higher than the increases due

Table 2—Fatty acid composition of frankfurters either not irradiated (0 kGy) or irradiated with 1 and 5 kGy gamma rays.

	0 mo			3 mo		
Fatty acid	**0 kGy**	**1 kGy**	**5 kGy**	**0 kGy**	**1 kGy**	**5 kGy**
C14:0	1.36 ± 0.03 a[A]	1.36 ± 0.02 a	1.35 ± 0.04 a	1.36 ± 0.01 a	1.36 ± 0.00 a	1.36 ± 0.01 a
C16:0	21.07 ± 0.19 a	21.14 ± 0.14 a	21.07 ± 0.21 a	21.18 ± 0.16 a	21.13 ± 0.04 a	21.10 ± 0.06 a
C16:1c	2.22 ± 0.02 b	2.21 ± 0.01 b	2.21 ± 0.02 b	2.26 ± 0.01 a	2.26 ± 0.01 a	2.26 ± 0.01 a
C17:0	0.44 ± 0.01 a	0.44 ± 0.00 a	0.44 ± 0.01 a	0.44 ± 0.01 a	0.44 ± 0.00 a	0.44 ± 0.00 a
C17:1c	0.30 ± 0.01 b	0.30 ± 0.01 b	0.30 ± 0.01 b	0.31 ± 0.02 ab	0.32 ± 0.01 a	0.32 ± 0.01 a
C18:0	10.70 ± 0.03 a	10.70 ± 0.03 a	10.71 ± 0.04 a	10.75 ± 0.10 a	10.70 ± 0.02 a	10.74 ± 0.03 a
C18:1t	1.21 ± 0.01 c	1.21 ± 0.01 bc	1.28 ± 0.01 a	1.22 ± 0.02 bc	1.23 ± 0.01 b	1.29 ± 0.01 a
C18:1t (% of sample)	0.29 ± 0.01 b	0.29 ± 0.01 b	0.31 ± 0.01 a	0.29 ± 0.01 b	0.29 ± 0.00 b	0.31 ± 0.01 a
C18:1c	39.66 ± 0.12 a	39.62 ± 0.08 a	39.68 ± 0.18 a	39.43 ± 0.38 a	39.59 ± 0.04 a	39.61 ± 0.04 a
C18:2n6c	19.09 ± 0.05 a	19.07 ± 0.04 a	19.01 ± 0.04 ab	19.10 ± 0.10 a	19.04 ± 0.07 ab	18.97 ± 0.04 b
C20:0	0.17 ± 0.00 a	0.17 ± 0.00 a	0.17 ± 0.00 a	0.17 ± 0.00 a	0.17 ± 0.00 a	0.17 ± 0.00 a
C20:1n9	0.79 ± 0.02 a	0.79 ± 0.01 a	0.79 ± 0.01 a	0.79 ± 0.01 a	0.79 ± 0.01 a	0.79 ± 0.01 a
C18:3n3	1.45 ± 0.01 a	1.46 ± 0.01 a	1.44 ± 0.01 ab	1.44 ± 0.01 ab	1.44 ± 0.01 ab	1.43 ± 0.01 b
C21:0	0.21 ± 0.01 a	0.20 ± 0.00 a	0.20 ± 0.01 a	0.20 ± 0.00 a	0.20 ± 0.01 a	0.20 ± 0.01 a
C20:2	0.61 ± 0.01 a	0.61 ± 0.01 a	0.61 ± 0.01 a	0.61 ± 0.01 a	0.60 ± 0.00 a	0.60 ± 0.00 a
C22:1n9	0.32 ± 0.01 ab	0.32 ± 0.01 b	0.33 ± 0.01 ab	0.33 ± 0.01 a	0.33 ± 0.00 ab	0.33 ± 0.01 ab
C23:0	0.40 ± 0.01 a	0.39 ± 0.01 ab	0.40 ± 0.01 ab	0.39 ± 0.00 c	0.38 ± 0.01 c	0.39 ± 0.00 bc
Total FA (% of sample)	23.79 ± 0.70 a	23.79 ± 0.46 a	23.90 ± 0.67 a	23.96 ± 0.17 a	23.84 ± 0.10 a	24.11 ± 0.29 a
MUFA	44.50 ± 0.13 a	44.46 ± 0.09 a	44.59 ± 0.18 a	44.34 ± 0.36 a	44.53 ± 0.05 a	44.61 ± 0.04 a
PUFA	21.15 ± 0.06 a	21.14 ± 0.04 a	21.06 ± 0.04 ab	21.16 ± 0.10 a	21.09 ± 0.06 ab	21.00 ± 0.03 b
TUFA	65.66 ± 0.19 a	65.60 ± 0.12 a	65.65 ± 0.22 a	65.50 ± 0.26 a	65.61 ± 0.04 a	65.62 ± 0.06 a
TSFA	34.34 ± 0.19 a	34.40 ± 0.12 a	34.35 ± 0.22 a	34.50 ± 0.26 a	34.39 ± 0.04 a	34.38 ± 0.06 a
TUFA/TSFA	1.91 ± 0.02 a	1.91 ± 0.01 a	1.91 ± 0.02 a	1.90 ± 0.02 a	1.91 ± 0.00 a	1.91 ± 0.01 a
C16:1t/C16:1c	0.14 ± 0.00 b	0.14 ± 0.00 b	0.14 ± 0.00 b	0.15 ± 0.00 a	0.15 ± 0.00 a	0.15 ± 0.00 a

Notes: After irradiation, the samples were stored at 4 °C for 3 mo. Fatty acids were expressed as percentages of total fatty acids unless otherwise stated.
[A]The numbers are means followed by standard deviations ($n = 4$). Means with same letter within the same rows are not significantly different (Duncan's multiple range test, $P < 0.01$).
MUFA = mono unsaturated fatty acid; PUFA = poly unsaturated fatty acid; TUFA = total unsaturated fatty acid; TSFA = total saturated fatty acid.

to irradiation. For example, *trans* fatty acid contents of Japanese cattle beef ranged from 1.9% to 6.8% of the total fatty acid (Matsuzaki and others 1998). *Trans* fatty acid content (C18:1 *trans*) varied considerably in beef samples obtained from different countries ranging from 2.8% to 9.5% of total fatty acid (Aro and others 1998). Seasonal factors, differences in feeds, and age of animals may account for the difference in *trans* fatty acid content. Similarly, the variation in unsaturated fatty acids of meat and meat products was also much larger than the changes caused by 5 kGy irradiation in the current study. Furthermore, it appears that there was an increase in *trans* fat content of ground beef during storage. The increase in *trans* fat (based on total fatty acid) in ground beef with time in storage was much greater (8.7% to 9.3%) than that caused by irradiation (1.5% to 2%). Of course, the variation in *trans* fat in frankfurters would be even larger due to the difference in ingredients. Aro and others (1998) found that *trans* fatty acid content varied from 0.4% to 5.3% of total fatty acids among sausages obtained from different countries. Therefore, even though we found a significant increase in *trans* fatty acids due to irradiation in ground beef and frankfurters, the changes were trivial.

Although in the current study radiation doses of 1 and 5 kGy were used to treat ground beef and frankfurters, commercially, irradiation is commonly applied at doses close to 1 kGy even though higher (4.5 kGy) doses are permitted by federal authority. Therefore, the high dose (5 kGy) used in the present study represented the worst scenario while 1 kGy may be more commonly used. Our results found that irradiation at 1 kGy most often did not affect fatty acid composition and the changes caused by 5 kGy irradiation were minimal compared to natural variations.

Conclusions

Our results demonstrated that ground beef and frankfurters irradiated at 5 kGy had slightly but statistically significant higher C18:1 *trans* fatty acid than the nonirradiated samples and irradiation at 1 kGy had no effect on C18:1 *trans* fatty acids. Irradiation did not have any significant effect on C16:1 or C18:2 *trans* fatty acids. Irradiation caused a slight decrease in poly-unsaturated fatty acids and the effect was amplified after storage. Taking the variations in *trans* fatty acid content in meats due to season, feed, age of animal, and storage into account, the effect of irradiation on fatty acid composition at the doses we tested was minimal.

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